ANALOG DEVICES
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Passive Component Selection and Dynamic Modeling for the 2S80 Series Resolver-to-Digital Converters

by Mark L. Schirmer

The 2S80 series of resolver-to-digital converters are unprecedented in their flexibility. This is a direct result of the use of external passive components to set the dynamic characteristics of the converter. This software package simplifies the computation of the values of these components. In addition, the closed loop transfer function and step responses (positional and velocity) can be computed and graphically displayed. The software also allows for component values to be adjusted and the resulting impact on the converter dynamics modeled.

The software can be used as a design tool for all options of the following devices:*

AD2S80A Variable Resolution,
Monolithic Resolver-to-Digital Converter (DIP)

AD2S81A Low Cost,
Monolithic 12-Bit Resolver-to-Digital Converter

AD2S82A Variable Resolution,
Monolithic Resolver-to-Digital Converter (PLCC)

AD2S83 Variable Resolution,
Monolithic Resolver-to-Digital Converter with High Quality Velocity Output

The user needs only to specify the reference frequency and the desired digital resolution for the converter. Optionally, values for the tracking bandwidth and maximum tracking rate may be entered, otherwise default values may be accepted. Throughout the software, simple on-line help screens are offered minimizing the need to reference the component data sheet and/or program documentation.

*This software is also applicable to the earlier generation 2S80, 2S81, and 2S82. Please see item 3 under "STARTING THE PROGRAM" on page 2.

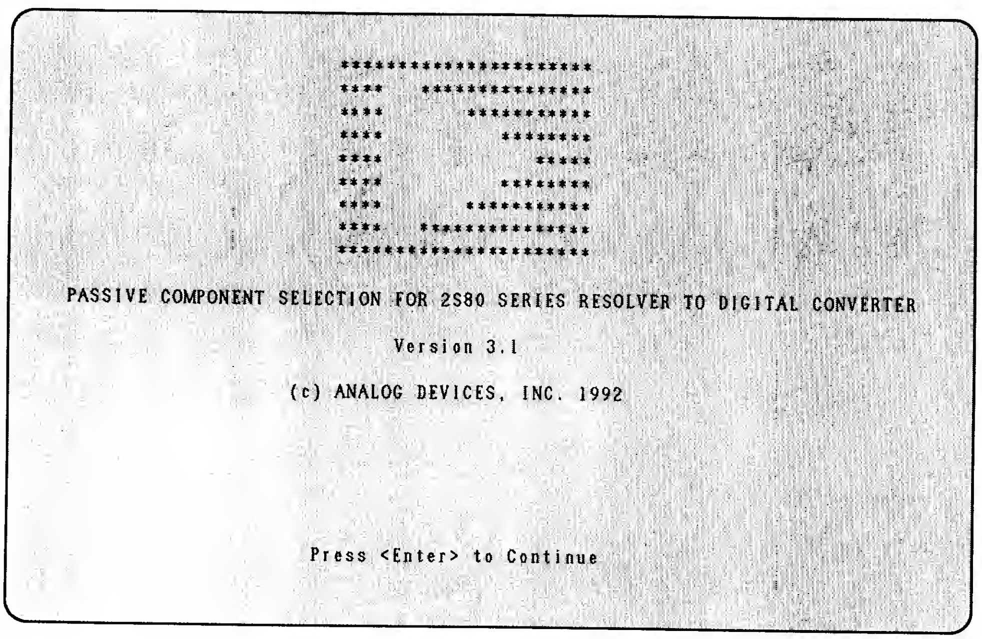
SYSTEM REQUIREMENTS

- IBM PC/XT/AT,† PS/2,† or "Compatible" Running MS-DOS‡ Version 2.0 or Higher
- 256K RAM Available Memory
- Graphics Display/Adapter (Monochrome, CGA, MCGA, EGA, VGA, or Hercules)
- 1 Floppy Disk Drive (5.25" 360KB Format)
- 8087/80287/80387 Math Coprocessor Recommended (Not Required)

STARTING THE PROGRAM

1. Boot up the PC with MS-DOS.
2. Insert the supplied floppy disk into a 360KB 5.25" drive.
3. From the DOS prompt, type "n:AD2S80" followed by <Enter> (<Return> on some keyboards) where "n" is the drive address. For example, if the PC was booted from drive C: and the software is installed on drive A:, the user would enter:

   C:> A:AD2S80 followed by <Enter>
4. The opening screen of the program should now be displayed:



5. Press <Enter> to move to model # selection screen.

If the message "Sorry . . . No Graphics Card Recognized" is displayed, one of the graphics displays/adapters listed in SYSTEM REQUIREMENTS was not found. Your hardware will have to be reconfigured in order to run the software.

RUNNING THE PROGRAM

Press the <Enter> key to clear the opening screen and move to the passive component selection procedure.

NOTE: <Ctrl> + <Break> may be pressed at any time to exit the program.

†IBM PC/XT/AT and PS/2 are trademarks of International Business Machines Corp.
‡MS-DOS is a registered trademark of Microsoft Corporation.

If the software is being run on a machine with either a VGA, EGA, or High Resolution Monochrome (MCGA) graphics adapter, the prompt "Disable Color in Graphics Displays [Y/N/?]?" will be displayed. Entering a "Y" followed by <Enter> will prevent large colored (or gray for the MCGA) areas from being displayed so that useful screen dumps can be made using the PC's <PrintScrn> key. This is necessary because some printers map one or more colors to black giving unpredictable results. Entering a "N" or pressing <Enter> with no entry will give normal color displays. Entering "?" or any character other than "Y" or "N" will give a help screen. Please note that the GRAPHICS statement from DOS must be executed prior to running the software in order to enable graphics screen dumps.

PASSIVE COMPONENT SELECTION

In response to the prompts, the following values should be entered followed by <Enter>:

i. Reference Frequency

ii. Closed Loop Bandwidth

iii. Resolution – (Enter 12 bits for the 2S81)

iv. Maximum Tracking Rate

v. Value of Resistor R1

In the case of parameters i. and iii., pressing <Enter> with no entry will display a context sensitive "Help" screen. For parameters ii., iv. and v., pressing <Enter> with no entry will accept a default value; the "Help" screen can be accessed by entering a "0" followed by <Enter>. In all cases, entry of unacceptable values will generate an informative error message.

The correct values for the passive components given the input parameters specified will be displayed in a tabular format as shown below.

```
      PASSIVE COMPONENT VALUES FOR 2S80 SERIES RESOLVER-TO-DIGITAL CONVERTERS

Reference Frequency:  1000  Hz           Closed Loop Bandwidth:  200 Hz
Maximum Tracking Rate:    62.5 rev/sec   Digital Resolution:  14  bits
Small Signal Step Response Settling Time:  29.2 ms

R1 & C2 FITTED                            R1 & C2 OMITTED

R 1=  24.0   Kohm                           N/A
R 2=  24.0   Kohm                           R 2= 100.0    Kohm
R 3= 100.0   Kohm                           unchanged
R 4=  33.0   Kohm                           R 4=  99.0    Kohm
R 5=  75.0   Kohm                           unchanged
R 6=  56.0   Kohm                           unchanged
R 7=  68.0    ohm                           unchanged

C 1=    6.8   nF                            C 1>   9.1    nF
C 2=    6.8   nF                            N/A
C 3>    9.1   nF                            unchanged
C 4=    9.1   nF                            unchanged
C 5=   43.0   nF                            unchanged
C 6= 470.0    pF                            unchanged

F1 = Repeat Selection  F2 = Transfer Function  F3 = Step Response  F4 = Quit
```

The values listed are standard 5% tolerance values that will give the closest possible performance to the requirements input by the user. These requirements are also reproduced in the tabular summary. All values are computed using the procedure and designations (R1, C2, etc.) defined in the relevant component data sheet and as detailed in the appendix. Alternative values are given for the mode where R1 and C2 are omitted.

NOTE: The values given for the maximum tracking rate and closed loop bandwidth are the same as those input by the user. These values will be adjusted if the transfer function is computed and found

to exhibit different behavior. These adjusted values will be given when the tabular component summary is recalled after either the step response or transfer function is computed and displayed.

Once the component values are displayed, four options, selected by function keys <F1> through <F4>, are available to the user:

<F1> **Repeat Passive Component Selection Program** —user is prompted to reenter input parameters, starting with the reference frequency.

<F2> **Compute Transfer Function**—the closed loop transfer function of the converter is computed and plotted for the component values displayed.

NOTE: On PCs with slow clock speeds or without a math coprocessor, this computation may take several seconds.

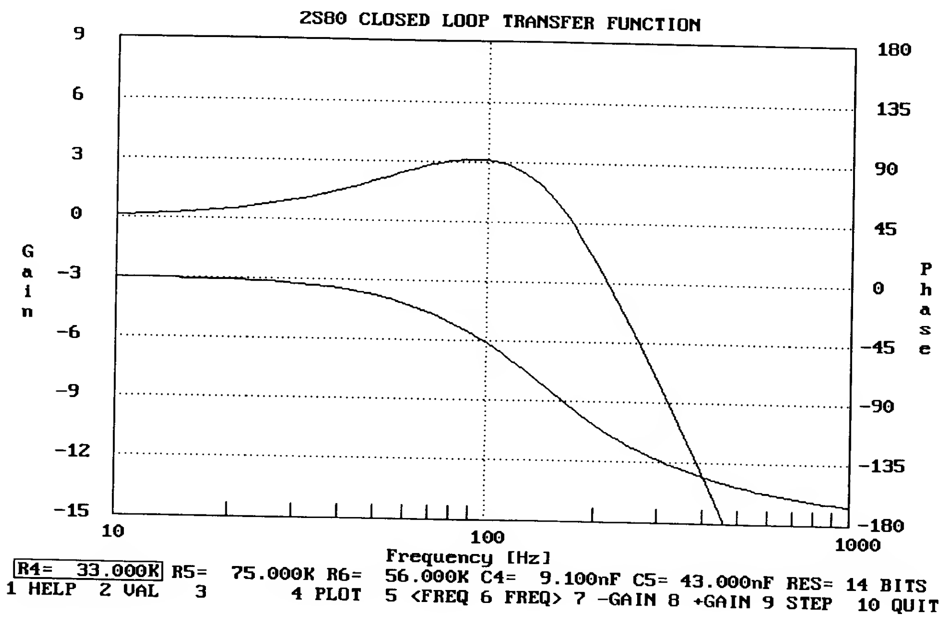
<F3> **Compute Small Signal Step Response**—the normalized response of the digital outputs to a step change in position input is computed and plotted for the component values displayed.

NOTE: On PCs with slow clock speeds or without a math coprocessor, this computation may take several seconds.

<F4> **Quit**—terminates program execution and returns the user to the DOS prompt.

TRANSFER FUNCTION

The closed loop transfer function is plotted on a logarithmic grid and consists of two curves, the Gain (in dB) and the Phase (in degrees). The resulting display should look similar to the following:



The closed loop transfer function is a measure of the response of the converter to dynamic inputs. The gain curve gives a measure of the amplitude response of the converter digital output to a small signal, sinusoidally varying about some fixed position, applied to the SIN and COS inputs. The phase curve is a measure of the temporal response of the converter, e.g., the phase delay from converter input to output. In both cases, the frequency axis of the transfer function refers to the frequency of the sinusoidally varying input signal, not to either the rotation speed (e.g., RPS) of the resolver or to the reference frequency.

As an example, consider a converter with a 200 Hz closed loop bandwidth as shown in the preceding transfer function plot. If a signal representative of a $\pm 1°$ sinusoidally varying position, oscillating at a 200 Hz rate about a fixed angle, is applied to the converter's SIN and COS inputs, we will observe a

sinusoidally varying output signal with an amplitude of approximately ±0.7° ($1/\sqrt{2} \times \pm 1°$), down by 3 dB from the input amplitude. In addition, the output variation will lag the input by approximately 110° or 1.5 milliseconds at 200 Hz.

It should be stressed that the transfer function is valid only for small variations in the input signal; the variations must not drive any component of the loop into saturation. For the 2S80 series of converters, these variations should be less than about 5°.

Modifying Passive Component Values

This portion of the program will allow the user to modify the values of components suggested by the earlier selection portion. The program is controlled by the PC function and cursor control keys. The functions are as follows:

<**F1**> Displays "Help" screen summarizing the operation of the function and cursor keys.

<**F2**> Displays the current component values and operating parameters in a tabular summary identical to the first section of the program.

<**F3**> (Not Used)

<**F4**> Recomputes and displays the transfer function. This key is normally used to update the graphic display after one or more of the passive component values have been altered through use of the cursor control keys. If the present graphic display does not correspond to the displayed passive component values, the message "PLOT INVALID: Press <F4>" will be displayed in the upper left corner of screen.

<**F5**> Adjusts the horizontal scale (frequency) of the transfer function display by shifting 1 decade to the left (i.e., lower frequencies).

<**F6**> Adjusts the horizontal scale (frequency) of the transfer function display by shifting 1 decade to the right (i.e., higher frequencies).

<**F7**> Adjusts the vertical scale of the transfer function gain plot by shifting upper and lower limits down by 3 dB.

<**F8**> Adjusts the vertical scale of the transfer function gain plot by shifting upper and lower limits up by 3 dB.

<**F9**> Displays the small signal step response of the converter for the selected component values. Note that on PCs running at low clock speeds or without math coprocessors this computation may take several seconds.

<**F10**> Terminates program execution and returns the user to the DOS prompt.

< ↑ > Increases the selected component value box through its standard 5% tolerance values.

< ↓ > Decreases the selected component value box through its standard 5% tolerance values.

<←> Moves the box indicating a selected component value (i.e., subject to adjustment with the < ↑ > and < ↓ > keys) to the left.

<→> Moves the box indicating a selected component value (i.e., subject to adjustment with the < ↑ > and < ↓ > keys) to the right.

CAUTION: Using this software, it is possible to manipulate the component values used with the 2S80 series to the extent that converter will not function correctly. Particular care should be taken in adjusting the resolution and the value for R4, the series input resistor to the integrator. These two parameters determine the level of internal hysteresis inside the converter used to stabilize the least significant bit (LSB) for static and low speed applications. Ideally, the two parameters should meet the constraint:

$$2^R \cdot R4 \approx 5.5 \times 10^8 \ bit\text{-}\Omega$$

where R4 is in ohms and R is the resolution of the converter (10, 12, 14, or 16 bits). Higher values of

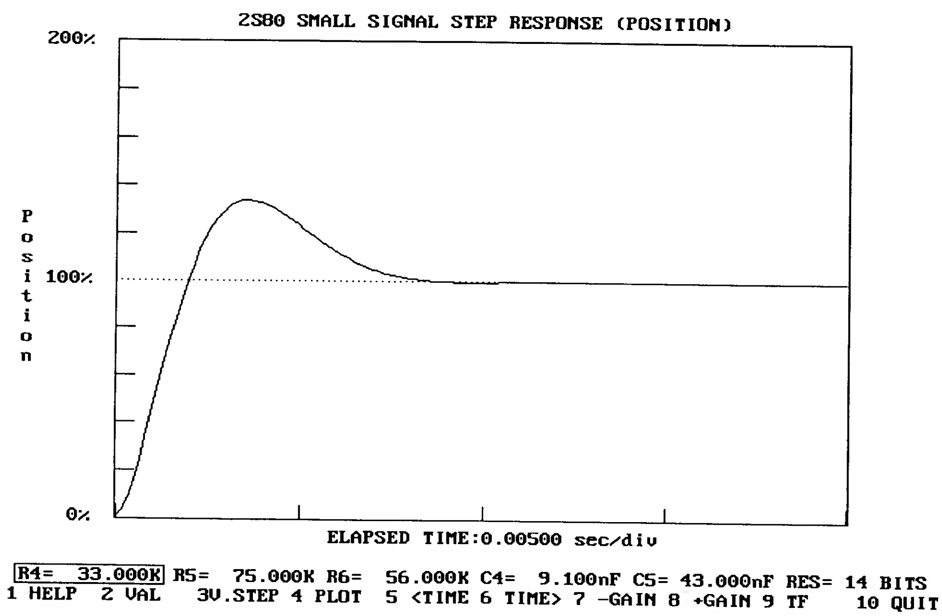
this product will yield less hysteresis possibly leading to flicker of the LSB at low speeds. Lower values will give good stability but compromise the repeatability of the outputs.

In addition, the frequency at which the transfer function crosses −3 dB (the bandwidth) should be compared with the reference frequency. If the ratio of the reference frequency to the bandwidth is less than about 2.5:1, the converter may not be stable and excessive ripple may be observed on the analog velocity signal.

STEP RESPONSE

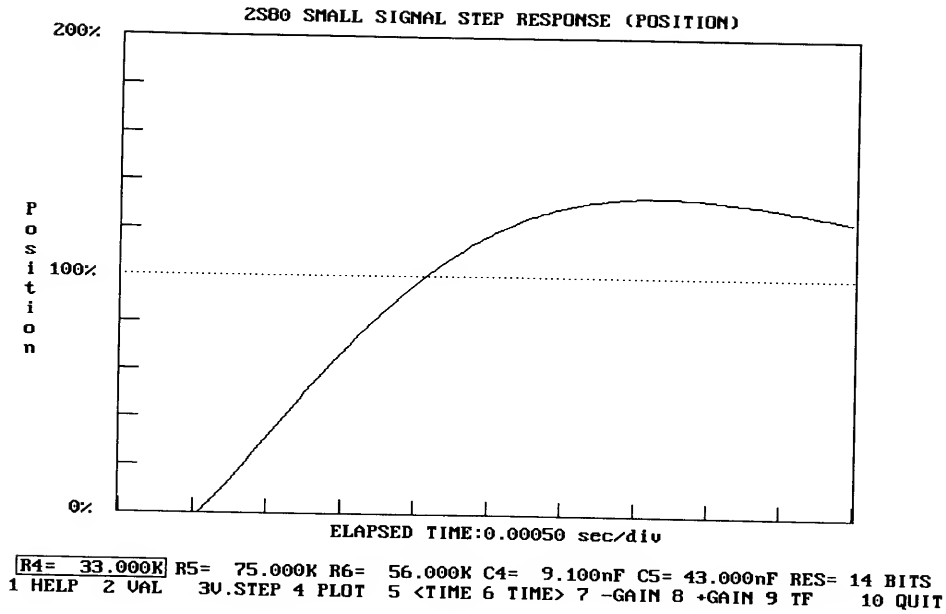
The step response of the converter is a measure of the response of the output of the converter to instantaneous changes in input position applied to SIN and COS. Such conditions may occur in multiplexed systems or applications with low inertia and high acceleration. The software has provisions for calculating responses of the both the position output and the analog velocity output to steps in input position. NOTE: The response of the analog velocity output of the converter to a velocity step is exactly the same as the response of the position output to a position step.

As is the case for the transfer function computation, the step response models generated by this program are valid only for small signal changes. For the 2S80 series, the largest step that can be applied without saturating any of the loop components is approximately 10 degrees, although the model gives good qualitative predictions for steps up to about 20 degrees. An example plot of the step response is given below:

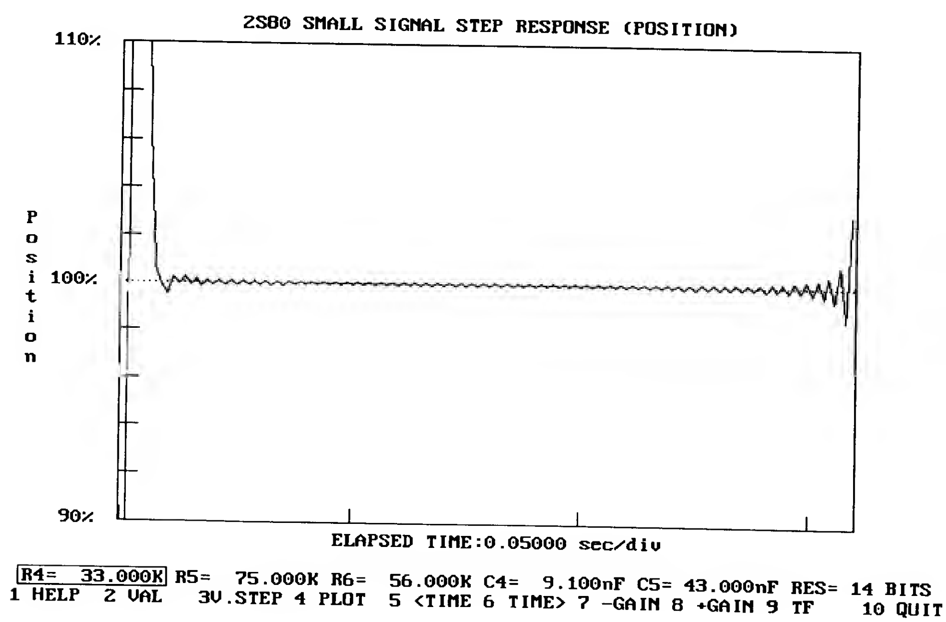


Both the position and velocity step responses are calculated using numerical Fourier transform convolution techniques on the transfer function. Because of both round-off errors in the PC and limitations of the frequency of sampled data in the computations, some artifacts may be introduced in the step response. The user should be aware of the following:

1. If the displayed positional step response does not start at 0% (0 V for the velocity step response) and at zero time, the total time displayed on the horizontal axis of the plot is too short to allow for accurate computations. The user should increase the total time interval by pressing <F6> [TIME>] until the response starts at 0% (0 V). This will rescale the limits internal to the calculation and result in a valid display. An example of an improperly scaled plot follows:

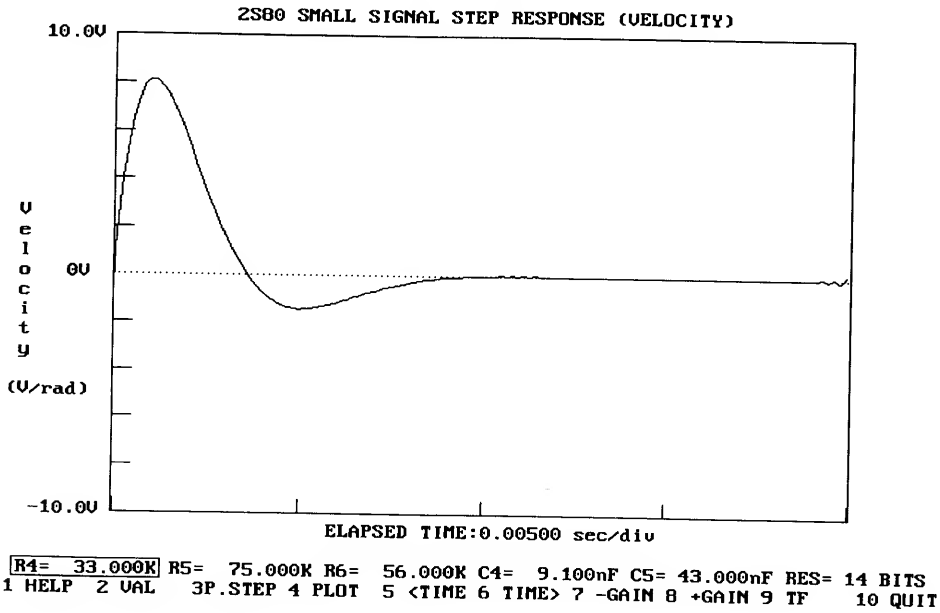


2. If apparent high frequency noise or "ringing" is observed on the displayed step response curve for long time scales, the total time displayed on the horizontal axis of the plot is too long for accurate computations. The user should decrease the total time interval by pressing <F5> [<TIME] until the response is stable over the entire time interval. An example of an improperly scaled plot exhibiting this problem is given below:



3. The positional step response is a relative calculation, hence the dimensionless vertical scale on the plot. The display shows the output position as a percentage of the magnitude of the input step. For example, if the input position steps from 15° to 20°, the 0% level corresponds to 15° and the 100% level to 20°, the response is normalized for the 5° input step. Please note that the calculation is only valid for steps less than approximately 10 degrees.

4. The velocity step response vertical scale is relative with the units [volts/radian] where 1 radian = 57.3°. In order to estimate the velocity response of the converter to an *x* radian position step, the readings should be multiplied by *x* to yield velocity values in volts. Please note that the actual velocity signal on the 2S80 series is constrained to less than approximately ±9 volts. As a result, if the model predicts a voltage peak greater than 9 volts for an *x* radian step, the step would in practice actually drive the converter into saturation, thus invalidating the calculation.



Modifying Passive Component Values

As in the case for the transfer function computation, the step response calculation is controlled by the PC's function keys. Their function closely parallels the transfer function section:

<F1> Displays "Help" screen summarizing the operation of the function and cursor keys.

<F2> Displays the current component values and operating parameters in a tabular summary identical to the first section of the program.

<F3> If the positional step response is displayed, this key will compute and display the velocity step response. Similarly, if the velocity step response is presently displayed, <F3> will generate the positional step response.

<F4> Recomputes and displays the step response. This key is normally used to update the graphic display after one or more of the passive component values have been altered through use of the cursor control keys. If the present graphic display does not correspond to the displayed passive component values, the message "PLOT INVALID: Press <F4>" will be displayed in the upper left corner of screen.

<F5> Adjusts the horizontal scale (time) of the step response display by reducing the total time displayed in a 5-2-1 sequence.

<F6> Adjusts the horizontal scale (time) of the step response display by increasing the total time displayed in a 1-2-5 sequence.

<F7> Adjusts the vertical scale of the step response plot:

Position: Increases vertical range by 10× symmetrically about 100% to a maximum of 0–200%.

Velocity: Increase vertical range by 10× to a maximum of ±100 V/radian.

<F8> Adjusts the vertical scale of the step response plot:

Position: Decreases vertical range by 10× symmetrically about 100% to a minimum of 99.1–100.1%.

Velocity: Increase vertical range by 10× to a maximum of ±0.1 V/radian.

<F9> Displays the closed loop transfer function of the converter for the selected component values. Note that on PCs running at low clock speeds or without math coprocessors this computation may take several seconds.

<F10> Terminates program execution and returns the user to the DOS prompt.

<↑> Increases the selected component value box through its standard 5% tolerance values.

<↓> Decreases the selected component value box through its standard 5% tolerance values.

<←> Moves the box indicating a selected component value (i.e., subject to adjustment with the <↑> and <↓> keys) to the left.

<→> Moves the box indicating a selected component value (i.e., subject to adjustment with the <↑> and <↓> keys) to the right.

APPENDIX

The following gives the relevant equations on which the calculations in this software are based.

Passive Component Selection

The program computes the values for R1 through R7 and C1 through C6 using the following equations. The closest 5% tolerance value to that suggested by the calculation is displayed. More detail on these relationships can be found in the relevant component data sheet. Note that all resistance values are specified in ohms and all capacitances are in farads.

$$R1 = R2 \leqslant 56\ k\Omega$$

$$C1 = C2 = \frac{1}{2\pi R1 f_{REF}}\ F$$

where f_{REF} = Reference Frequency [Hz].

$$R3 = 100\ k\Omega$$

$$C3 \geq \frac{1}{10^5 \times f_{REF}}\ F$$

The value of R4 depends on the configuration of the HF filter between the AC ERROR output and the DEMOD input. This filter may be either a bandpass configuration (R1, C2 fitted) or a simple high pass filter (R1, C2 omitted).

If R1 and C2 are fitted, then:

$$R4 = \frac{5.46 \times 10^8}{2^R}\ \Omega$$

otherwise with R1 and C2 omitted then:

$$R4 = \frac{1.64 \times 10^9}{2^R}\ \Omega$$

where R is the converter resolution (10, 12, 14, or 16 bits).

The tracking rate range of the converter is set by the resistor in series with the VCO input driven by the integrator output. This resistor is a function of the resolution of the converter as follows:

$$R6 = \frac{8 \times F_{VCO}}{T \times 2^{R}}\,\Omega$$

where T is the maximum tracking rate in revolutions/second [RPS], and F_{VCO} is the VCO rate in Hz/A.

The bandwidth selection components around the integrator are chosen to yield an optimally damped system ($\zeta = 0.707$). Note that indirectly (by virtue of their dependence on R6) the values of C4, C5, and R5 are function of the resolution and maximum tracking rate:

$$C4 = \frac{20.2}{R6 \times f_{BW}^{2}}\,F$$

$$C5 = 5 \times C4$$

$$R5 = \frac{4}{2 \times \pi \times f_{BW} \times C5}\,\Omega$$

For AD2S83, substitute

$$C4 = \frac{21}{R6 \times f_{BW}^{2}}$$

where f_{BW} is the closed loop bandwidth [Hz].

The phase compensation components for the VCO input are fixed with the following values:

$$C6 = 470\ pF$$
$$R7 = 68\ \Omega$$

For AD2S83, substitute

$$C6 = 390\ pF$$
$$C7 = 150\ pF$$
$$R7 = 68\ \Omega$$

The small signal step response settling time is approximated by the equation:

$$t_2 = \frac{5}{f_{BW}} \times \frac{R}{12}$$

Transfer Function

The closed loop positional transfer function of the 2S80 series is given by the equations:

$$f(s) = \frac{\theta_{OUT}}{\theta_{IN}}(s) = \frac{K_A m\omega_2(1 + s/\omega_2)}{s^3 + m\omega_2 s^2 + K_A m s + K_A m\omega_2}$$

where

$$\omega_2 = \frac{1}{R5 \times C5}$$

$$m = \frac{C4 + C5}{C4}$$

$$s = j\omega$$

$$K_A = \frac{54.6 \times F_{VCO}}{2^{R} \times R4 \times R6 \times (C4 + C5)}\ sec^{-2}$$

Note that in the previous equations, the transfer function is specified in terms of angular frequency [radians/second] rather than rotational frequency [Hz].

The passive component selection procedure for the 2S80 series is structured so that the phase margin of the loop is maximized and the damping is near optimal. In this instance the following relations are true:

$$K_A = \sqrt{m}\,\omega_2^2$$

$$\zeta = \frac{\sqrt{m}-1}{2}$$

$$\omega_{BW} \approx 4\,\omega_2$$

where K_A is the acceleration constant, ζ is the loop damping factor, and ω_{BW} is the loop bandwidth. It should be observed that the above relationships may not remain valid if component values are substantially altered from those generated by the passive component selection algorithm.

Step Response

The step response of the 2S80 series is given by the inverse Laplace transform of the closed loop transfer function convolved with the Laplace transform of a unit step.

The Laplace transform and its inverse are defined as:

$$\pounds\{F(t)\} = f(s) = \int_0^{\infty} e^{-st}\,F(t)dt$$

$$\pounds^{-1}\{f(s)\} = F(t) = \frac{1}{2\pi j}\int_{a-j\infty}^{a+j\infty} e^{st}f(s)ds$$

The transform of the unit step is given by:

$$\pounds\{\mu(t)\} = \frac{1}{s}$$

This gives the following expression for the positional step response of the 2S80 series:

$$P(t) = \pounds^{-1}\left\{f(s)\cdot\frac{1}{s}\right\} = \int_{a-j\infty}^{a+j\infty} \frac{K_A m\omega_2\,(1 + s/\omega_2)}{s^4 + m\omega_2 s^3 + K_A m s^2 + K_A m\omega_2 s}\,ds$$

This expression gives the response of the position output to a step change in input position. It should also be noted that the same relationship will hold for the response of the analog velocity signal to a step change in input velocity.

The velocity step response (velocity response to position changes) is given by a similar transformation, but using the velocity transfer function for the 2S80 series. The velocity transfer function can be derived from the positional transfer function by multiplying by the Laplace variable *s* and dividing by the VCO gain, K_{VCO}.

$$K_{VCO} = \frac{2 \times \pi \times F_{VCO}}{R6 \times 2^{R}} \left[\frac{\text{rad}}{\text{V} \cdot \text{sec}}\right]$$

$$V(t) = £^{-1}\left\{\frac{s \cdot f(s)}{K_{VCO}} \cdot \frac{1}{s}\right\} = \int_{a - j\infty}^{a + j\infty} \frac{K_A m \omega_2 \,(1 + s/\omega_2)}{K_{VCO}\,(s^3 + m\omega_2 s^2 + K_A m s + K_A m \omega_2)}\, ds$$

Note that the factor of *s* introduced by the velocity transfer function is cancelled by the 1/*s* term for the step function transform. This expression gives the response of the analog velocity signal (in volts) to a step change in input position.

For computational efficiency and general case applicability, rather than perform the integrations detailed above, the program actually uses Fast Fourier Transform (FFT) techniques to perform the calculations. The results, however, are the same as those that would be generated using the equations outlined above.